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Acoustic attenuation due to bi-modal size distributions of suspended sediment

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ABSTRACT

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Acoustic backscatter is a technique commonly used to remotely measure the concentration profile of suspended sediment. The technique generally involves an inversion, because the backscattered sound intensity depends upon the range dependent concentration and size distribution of the sound-scattering particles. This work examines the attenuation of sound due to particles, and in particular evaluates the relative contributions of viscous attenuation verses scattering attenuation as a function of the size of the particles. It is found that under some conditions viscous attenuation is dominated by smaller sized sediment and scattering attenuation is dominated by larger size sediment, but this result is not true in general, and depends upon the particular particle size distribution.

ADDITIONAL INDEX WORDS: *hydro-acoustics, suspended sediment*

INTRODUCTION

The profiles of suspended sediment concentration and size are sometimes measured using acoustic backscatter techniques. The principle underlying the measurement technique is to transmit a pulse of sound energy into water and interpret the range-gated sound pressure received back at the same transducer, as described by Hay (1983). For example, acoustic systems with frequencies of 1 to 5 MHz were used by Libicki et al. (1989) in the deep ocean and by Hanes et al. (1988) in the shallow nearshore zone, following the concepts reviewed by Thorne and Hanes (2002). Interest in extracting sediment concentration from the backscatter signal strength has recently increased in a variety of environments with the widespread use of commercial Acoustic Doppler Current Profilers (ADCP's). For example, Gartner (2004), and Hoitink and P. Hoekstra (2005) report using ADCP's to measure suspended sediments, mainly in the clay to silt size ranges, in coastal environments. An interesting topic of scientific discussion that has emerged in recent years involves the impact and importance of enhanced viscous dissipation of sound due to fine sediment [e.g. Sassi et al. (2012), Hanes (2012, 2013), Guerrero et al. (2014)]. The phenomenon of enhanced viscous dissipation due to small particles in water was initially documented by Urick (1948) and Flammer (1962). Until recently the viscous dissipation due to water and sediment had generally been ignored in acoustic interrogations of suspended sediment because the attenuation of sound due to scattering by particles was much larger than viscous attenuation. In many of the environments being investigated, such as the nearshore zone, the sediment was typically well-sorted sand. In other environments, however, bi-modal suspended sediment size distributions are sometimes present. In rivers, for example, Wright et al. (2010), through largely empirical means, measured the concentrations of suspended silt and clay (combined) and suspended sand in the Colorado River using a single frequency backscatter system. Their success is probably due to conditions in which the clay/silt sized fraction dominated the viscous dissipation of sound energy and the sand sized fraction dominated the backscattering of sound. Their success probably also depended on the relatively stable size distribution over time, and the relatively homogeneous suspended sediment concentration along the acoustic beam path, which was directed approximately horizontally from the river bank toward the center of the river. Moore et al. (2013) inverted attenuation measurements from a multi-frequency system with varying degree of success, when compared with particle size measured with a laser diffraction instrument. Similarly, Latosinski et al. (2014) inverted vertical profiles in a river by assuming vertically homogeneous, *known* size sediment. Routine inversion of vertical profiles of sediment backscatter still remains elusive, in part due to the wide range of particle characteristics, and in part due to the common bi-modality or broad range of the sediment size distribution in nature. This context motivates the present work.

METHODS

The theory of sound scattering from an aqueous suspension of particles and the practice of using acoustic backscatter to measure suspended sediments has been previously reviewed by

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Thorne and Hanes (2002) and updated by Thorne and Hurther (2014). A typical goal is to interpret the measured backscattered sound pressure to calculate the range-dependent concentration and size of the suspended particles. The backscattered sound pressure measured at a transducer is due to the integration of sound scattering and attenuation due to the particles and fluid along the two-way acoustic path between the transducer and the ensonified volume. Due to the variations in sediment along the sound path, an inversion is typically required to convert the measured backscattered pressure to the range dependent concentration and size of the suspended particles. When a single frequency acoustic system is employed, there is a fundamental shortcoming in that the backscattered sound depends upon both the concentration and the size of the suspended sediment, even if the size of the grains is uniform. This leads to non-unique inversions for sediment concentration and size. This shortcoming can be overcome in theory through the use of two or more acoustic frequencies, although in practice this has proven quite challenging. More commonly the size of the suspended sediment is measured independently and assumed not to vary significantly in space or time.

Key parameters that describe acoustic-particle interactions are the attenuation due to particles, and the backscatter target strength. The backscattering strength of the target particles is characterized by the backscatter form factor, *f*, defined so that the acoustic scattering *intensity* is proportional to particle area multiplied by f^2. The total attenuation derives from three sources: the viscous attenuation due the clear fluid, the viscous attenuation due to the interactions between particles and fluid, and the (non-backwards) scattering of sound due to the particles. Typical values for the viscous attenuation due to sediment, the scattering attenuation due to sediment, and the sediment backscatter form factor, all for uniform sized sediment, are shown in Figure 1 (from Hanes, 2012), as a function of sediment size, for three different sound frequencies. Of particular relevance here is the peak in viscous attenuation due to fluid-sediment interactions for the smaller grain sizes, which can for some cases cause greater attenuation than that due to the scattering of sound from particles.

The backscatter form function and the attention depend strongly on grain properties such as size and shape, and weakly upon sediment density and water viscosity for most environments, with any particular acoustic instrumentation system. If there exists a distribution of grain sizes, then the attenuation and backscatter must be appropriately integrated over the grain size distribution such as described, for example, by Thosteson and Hanes (1998) or Moate and Thorne (2009, 2012). The total attenuation from a distribution of particle sizes is additive, weighted by the concentration of each size. In contrast to the attenuation, the total backscatter is calculated as the square-root of the sum of squared backscattered pressure due to individual size classes, and thus depends upon the square root of concentration for each size sediment.

In the next section the theoretical acoustic attenuation will be calculated for various distributions of grain sizes. The grains are all considered to be the same material, and spheres, with only size varying. All of the examples show results for 500 KHz sound and a bi-normal distribution (the sum of two normal distributions) of sediment size by mass, with one peak of the distribution in the clay/silt range, and one in the sand size range. The standard deviation of each normal distribution is equal to 25% of the mean size. For illustrative purposes, the fine and coarse fractions have equal mass concentration in all of the examples to be shown.

Acoustic attenuation is often characterized by the natural logarithm of the sound pressure at two locations separated by a unit of distance, expressed for example, as Nepers/cm, where Nepers= $\ln(P_2/P_1)$. Nepers are similar to Decibels except that Decibels are normally defined using the signal power (pressure squared for acoustics) and the base 10 logarithm, so Decibels=20 $\log_{10}(P_2/P_1)$. For conversion, 1 Neper = 8.686 Decibels. All the attenuation values in this work are normalized by volume concentration, and are expressed as Nepers/cm/C, where C is volume concentration.

RESULTS

Figure 2 introduces the conceptual implications of a bi-modal sediment size distribution. For comparison with uniform sized grains, the red curve is the total (viscous plus scattering) attenuation for sediment with uniform grain size, as a function of particle radius. The red curve clearly shows the peak in viscous attenuation related to fine grains and the peak in scattering attenuation related to coarse grains, as was demonstrated previously in Figure 1. The red circles indicate the total attenuation if the uniform sediment radius was 1 micron, or if the uniform sediment radius was 200 microns. The green curve (and right axis) shows the cumulative bi-modal sediment size distribution, where sand mean radius is 200 microns and clay mean radius is 1 micron. The blue curve is the total attenuation for the bi-normal sediment size distribution. Note that for this particular example the attenuation increases sharply due to viscous dissipation from the fine sediment, and then it increases a bit more due to scattering from the coarse sediment. The blue x at the right side of the blue curve is the attenuation that would be obtained by simply summing the two red circles, as if half the

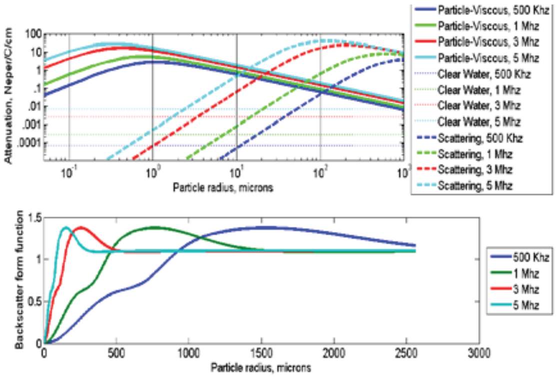

Figure 1: Upper panel: Normalized attenuation coefficients as a function of particle radius. Lower panel: Backscatter form function as a function of particle radius.

sediment was 1 micron radius and half was 200 microns radius. For this example the total attenuation is primarily due to the viscous attenuation due to the fine sediment. But this is not a general result; rather the relative importance of viscous attenuation relative to scattering attenuation depends upon the shape of the size distribution of the sediment. In the next section a range of size combinations will be considered.

Figure 3 shows the total attenuation for a range of bi-normal size distributions, where one peak lies in the size range of clay/silt (diameter between 1 micron and 63 microns) and the other peak lies in the size range for sand (diameter 64 microns to 3 mm). The horizontal axis is diameter of the coarse fraction and the vertical axis is diameter of fine sediment. The horizontally aligned bright area is due mainly to the viscous dissipation peak near 1 micron, and the vertically aligned bright area is due mainly to the peak in the scattering around 3 mm. There are combinations of sizes where the attenuation is dominated by either the viscous dissipation due to fine sediment or the scattering attenuation of the coarse sediment. But there are other combinations of sizes where both the fine and the coarse sediment contribute to the attenuation. It should be noted that all the results presented are based on equal concentrations of fine and coarse sediments. If the concentration varied with sediment size in a more general sense then the shape of the size distribution could significantly alter the results.

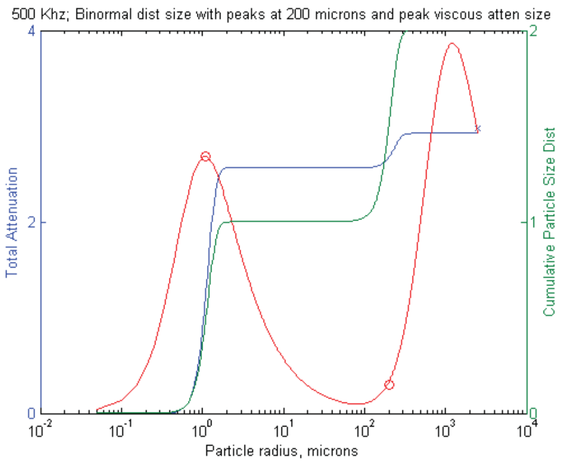

Figure 2: Attenuation due to a bi-modal mixture of 1 micron radius clay and 200 micron radius sand, with 500 KHz sound.

of Figure 3. If all attenuation were due to viscous dissipation the ratio is 0 (dark blue) and if all were due to scattering the ratio is 1 (dark red). The bluer shaded colors indicate where The relative importance of viscous and scattering attenuation is demonstrated by the ratio of the scattering attenuation to the total attenuation, as shown for Figure 4, for the same conditions viscous dissipation dominates, the red shaded colors indicate where scattering attenuation dominates, and the aqua-yellow shades show where both viscous and scattering attenuation are important.

DISCUSSION

Hanes (2012, 2013) considered an idealized uniform suspension with only two widely different particle sizes. He showed that in order for the attenuation and backscatter to be decoupled from each other for this situation, the attenuation needs to be dominated by the fine sediment while the backscatter is dominated by the coarse sediment. The present simulations examine this possibility for bi-normal distributions of sediment size, where one peak is in the size range of clay/silt and the other in the size range of sand.

CONCLUSIONS

These simulations provide support for the idea that under certain conditions a single frequency acoustic backscatter system can, in theory, measure the suspended sediment concentration of both the clay/silt size range and the sand size range. The explanation is essentially similar to that provided previously: the fine sediment can dominate the attenuation while the coarse sediment dominates the backscatter. This work also points to the sensitivity of acoustic attenuation to the size distribution of the suspended sediment, implies that the explanation provided above is not a general result for size distributions different from those simulated. This suggests that independent measurements of the particle size distribution (e.g. using laser diffraction), and multi-frequency measurements of acoustic attenuation could be very valuable to field measurements of acoustic backscatter, in order to measure the concentration and size profiles of suspended sediment.

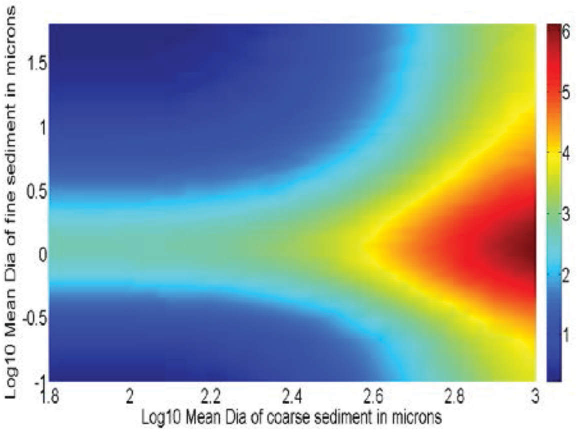

Figure 3: Total attenuation for a bi-normally distributed mixture of clay/silt and sand, for 500 KHz sound.

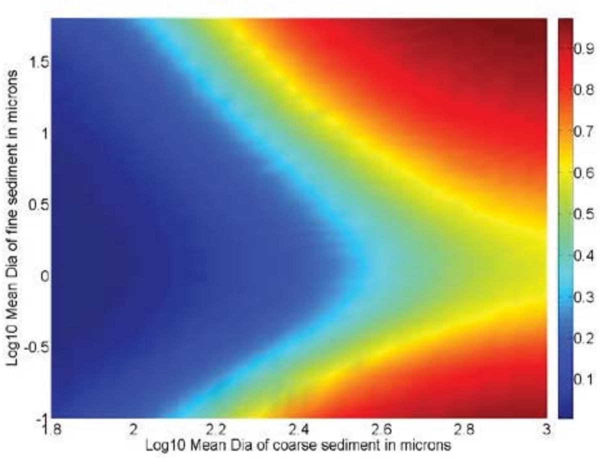

Figure 4: Ratio of the scattering attenuation to the total attenuation for a bi-normally distributed mixture of clay/silt and sand, for 500 KHz sound.

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